

# Is the Cosmic Transparency Spatially Homogeneous?

Jun Chen<sup>a,b</sup>, Puxun Wu<sup>c</sup>, Hongwei Yu<sup>a,c,\*</sup> and Zhengxiang Li<sup>a</sup>

<sup>a</sup>*Institute of Physics and Key Laboratory of Low Dimensional  
Quantum Structures and Quantum Control of Ministry of Education,  
Hunan Normal University, Changsha, Hunan 410081, China*

<sup>b</sup>*Department of Physics and Electronic Science,  
Hunan University of Arts and Science, Changde, Hunan 415000, China*

<sup>c</sup>*Center for Nonlinear Science and Department of Physics,  
Ningbo University, Ningbo, Zhejiang 315211, China*

## Abstract

We study the constraints on the cosmic opacity using the latest BAO and Union2 SNIa data in this paper and find that the best fit values seem to indicate that an opaque universe is preferred in redshift regions  $0.20 - 0.35$ ,  $0.35 - 0.44$  and  $0.60 - 0.73$ , whereas, a transparent universe is favored in redshift regions  $0.106 - 0.20$ ,  $0.44 - 0.57$  and  $0.57 - 0.60$ . However, our result is still consistent with a transparent universe at the  $1\sigma$  confidence level, even though the best-fit cosmic opacity oscillates between zero and some nonzero values as the redshift varies.

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\* Corresponding author: hwyu@hunnu.edu.cn

## I. INTRODUCTION

The present accelerating cosmic expansion is discovered firstly from the observation of Type Ia supernova (SNIa) [1, 2] since it revealed that the supernova are fainter than expected from a decelerating expanding universe under the assumption that the universe is transparent. However, the universe may be opaque due to that there may exist sources for photon attenuation, such as absorption or scattering of gas and plasma in and around galaxies. Furthermore, if dark matter is an axion or axion-like particle, photons propagating in extragalactic magnetic fields may oscillate into axion or axion-like particle. It has been shown that this axion-photon mixing may account for the dimming of SNIa [3, 4] without the need of dark energy or modified gravity.

The photon attenuation inevitably leads to a violation of the distance duality (DD) relation, also called the Etherington relation [5]:

$$D_L = (1 + z)^2 D_A, \quad (1)$$

which is built on two assumptions: the conservation of photon number and Lorentz invariance. Here,  $z$  is the redshift,  $D_L$  and  $D_A$  are the luminosity distance and the angular diameter distance, respectively. If one can have both  $D_A$  and  $D_L$  at the same redshift from observations, the DD relation can be tested directly [6–20]. From the Union2 SNIa, which provides the luminosity distance, and the galaxy cluster data giving the angular diameter distance, it has been found that the DD relation is consistent with the observations at the  $1\sigma$  confidence level when the elliptical galaxy cluster data [21] is used. However, the consistency occurs only at the  $3\sigma$  confidence level [22] for the spherical galaxy cluster data [23]. Thus, a violation of the DD relation is not excluded. This may be considered as a result of a breakdown of physics on which the DD relation is based upon [3, 24, 25].

Assuming that the photon travels on null geodesics, the cosmic opacity becomes the only source for the breakdown of the DD relation. Thus, observational data on  $D_L$  and  $D_A$  can give a constraint on the cosmic opacity. More et al. [26] have used the Sloan Digital Sky Survey (SDSS) and the Two Degree Field Galaxy Redshift Survey (2dFGRS) BAO data measured at redshifts  $z = 0.35$  and  $0.20$  [27] and SNIa data from [28] to constrain the opacity, and found that a transparent universe is favored and an opacity  $\Delta\tau < 0.13$  at the 95% confidence level for the redshift range between 0.2 and 0.35. Later, Avgoustidis et al. [6] studied the possible deviation from transparency by using the cosmic expansion history

$H(z)$  data [29] and the Union SNIa data [30], and found  $\Delta\tau < 0.012$  at the 95% confidence level between redshift 0.2 and 0.35, which is a factor of 2 stronger than what was obtained in [26].

Recently, the 6-degree Field Galaxy Survey (6dFGS) has reported a BAO detection in the low-redshift universe  $z = 0.106$  [31]. The WiggleZ Dark Energy Survey has released the baryon acoustic peak at redshifts  $z = 0.44, 0.6$  and  $0.73$  [32], and the Baryonic Oscillation Spectroscopic Survey (BOSS) has given a data point at  $z = 0.57$  [33]. Combining the WiggleZ dark energy Survey with 6dFGS, SDSS and BOSS, we now have seven BAO data points. Except for the data from BOSS, the other six data points have been shown in Tab. (3) in [32]. Furthermore, the SDSS BAO survey has released the latest results [34]. Therefore, it is of interest to re-examine the cosmic opacity using these latest BAO data and this is what we are going to do in this paper. The behavior of cosmic opacity in different redshift regions will be discussed in detail.

## II. THE COSMIC TRANSPARENCY

It follows from Eq. (1) that the transparency of the universe requires

$$\frac{(1+z_2)^2 D_A(z_2)}{(1+z_1)^2 D_A(z_1)} = \frac{D_L(z_2)}{D_L(z_1)}, \quad (2)$$

which is independent of cosmological models and so far, it has been applied to all analysis of the cosmological observations without any doubt. Its validity can however be tested observationally. In this regard, let us note that since BAO provides a standard ruler for direct measurement of the cosmic expansion history, therefore, we can obtain the angular diameter distance from BAO observation which is independent of photon attenuation. For BAO data, the acoustic parameter  $A(z)$  introduced by Eisenstein et al. [35]

$$A(z) = \frac{100 D_V(z) \sqrt{\Omega_m h^2}}{cz}, \quad (3)$$

is used usually, where  $\Omega_m$  is the matter density parameter,  $h = H_0/100$ , and the hybrid distance  $D_V$  relates with the angular diameter distance  $D_A$  through

$$D_V = \left( \frac{cz(1+z)^2 D_A^2}{H(z)} \right)^{\frac{1}{3}}. \quad (4)$$

Here  $H(z)$  is the Hubble expansion rate at redshift  $z$ . To test Eq. (2), we use, for convenience, the ratio of  $A$  instead of  $D_L$ . From Tab. (3) in [32] and the data from BOSS [33], we get the observed ratios of  $A$ , which are given in Tab. (I).

$\frac{A(0.2)}{A(0.106)}$	$\frac{A(0.35)}{A(0.2)}$	$\frac{A(0.44)}{A(0.35)}$
$0.928 \pm 0.058$	$0.992 \pm 0.046$	$0.979 \pm 0.077$
$\frac{A(0.57)}{A(0.44)}$	$\frac{A(0.6)}{A(0.57)}$	$\frac{A(0.73)}{A(0.6)}$
$0.937 \pm 0.073$	$0.995 \pm 0.055$	$0.959 \pm 0.064$

TABLE I: The ratio of the acoustic parameter  $A(z)$  obtained from Refs. [32, 33].

SN Ia has been found to be standard candles which can be used to make an independent direct measurement of the expansion history [1, 2]. Its luminosity distance can be determined by measuring energy per unit time per unit area received at a telescope. Thus, we can determine the right-hand side of Eq. (2) from SN Ia directly. In this paper, the Union2 SN Ia sample, which contains 557 data points, is used [36]. In order to obtain the luminosity distance at the corresponding redshift  $z$  of BAO data, we bin all SN Ia data in the redshift range  $[z - 0.05, z + 0.05]$  and the binned  $D_L$  at redshift  $z$  is

$$D_L^{bin} = \frac{\sum D_{L_i} / (\sigma_{D_{L_i}}^2 + \sigma_{S_i}^2)}{\sum 1 / (\sigma_{D_{L_i}}^2 + \sigma_{S_i}^2)}, \quad (5)$$

with  $\sigma_{D_L^{bin}}^2$  being

$$\sigma_{D_L^{bin}}^2 = \frac{1}{\sum 1 / (\sigma_{D_{L_i}}^2 + \sigma_{S_i}^2)}. \quad (6)$$

Here,  $\sigma_{D_{L_i}}$  is the uncertainty of the individual distance and  $\sigma_{S_i}$  is the corresponding systematic error. For the Union2 SN Ia sample, systematic errors have been compiled in Tab. (7) of [36].

If the universe is opaque, that is, there are some sources for photon attenuation, the observed luminosity distance derived from SN Ia will be modified and it will be larger than the true one. Let  $\tau(z)$  denotes the opacity between an observer at redshift  $z = 0$  and a source at  $z$ . The flux received from this source would be reduced by a factor  $e^{-\tau(z)}$ . The relation between the observed luminosity distance and the true one becomes [37]:

$$D_{L_{true}}^2 = D_{L_{obs}}^2 e^{-\tau(z)}. \quad (7)$$

Here,  $D_{L_{obs}}$  is obtained from SNIa data. Since BAO observation is not affected by the photon attenuation,  $D_{L_{true}}$  can be derived from BAO data. If the universe is transparent,  $\tau(z)$  is zero.

Because SNIa observation only releases the distance modulus data, which relates to the luminosity distance through

$$\mu = 5 \log D_L + 25, \quad (8)$$

the observed distance modulus also differs from the true one

$$\mu_{obs}(z) = \mu_{true}(z) + (2.5 \log e) \tau(z). \quad (9)$$

Thus, the distance modulus difference between two redshifts  $z_1$  and  $z_2$  is

$$\Delta\mu_{obs} = \mu_{obs}(z_2) - \mu_{obs}(z_1), \quad (10)$$

and then one can obtain

$$\Delta\mu_{obs} = 5 \log \frac{D_{L_{true}}(z_2)}{D_{L_{true}}(z_1)} + 2.5 \Delta\tau \log e, \quad (11)$$

where  $\Delta\tau = \tau(z_2) - \tau(z_1)$ . From the Union2 SNIa data and the binning method, we find  $\Delta\mu_{obs}$  at the redshift differences of BAO data and show them in Tabs. (II) and (III), which correspond to the case without and with systematic errors, respectively.

$\mu_{obs}(0.2) - \mu_{obs}(0.106)$	$\mu_{obs}(0.35) - \mu_{obs}(0.2)$	$\mu_{obs}(0.44) - \mu_{obs}(0.35)$
$1.332 \pm 0.094$	$1.439 \pm 0.101$	$0.606 \pm 0.116$
$\mu_{obs}(0.57) - \mu_{obs}(0.44)$	$\mu_{obs}(0.6) - \mu_{obs}(0.57)$	$\mu_{obs}(0.73) - \mu_{obs}(0.6)$
$0.533 \pm 0.160$	$0.079 \pm 0.188$	$0.598 \pm 0.188$

TABLE II: The SNIa distance modulus difference.

$\mu_{obs}(0.2) - \mu_{obs}(0.106)(sys)$	$\mu_{obs}(0.35) - \mu_{obs}(0.2)(sys)$	$\mu_{obs}(0.44) - \mu_{obs}(0.35)(sys)$
$1.332 \pm 0.120$	$1.430 \pm 0.123$	$0.621 \pm 0.137$
$\mu_{obs}(0.57) - \mu_{obs}(0.44)(sys)$	$\mu_{obs}(0.6) - \mu_{obs}(0.57)(sys)$	$\mu_{obs}(0.73) - \mu_{obs}(0.6)(sys)$
$0.533 \pm 0.195$	$0.082 \pm 0.232$	$0.601 \pm 0.236$

TABLE III: The SNIa distance modulus difference with systematic errors included.

Combining Eqs. (3, 4, 11) and using the fact that  $D_{L_{true}}$  can be deduced from BAO data, we have

$$\Delta\mu_{obs} = \frac{5}{2} \left( \frac{\Delta\tau}{\ln(10)} + 3 \log \frac{A(z_2)}{A(z_1)} - \log \frac{z_1^2(1+z_1)^2 H(z_1)}{z_2^2(1+z_2)^2 H(z_2)} \right). \quad (12)$$

The last term on the right hand side of the above equation shows that a cosmological model must be assumed to find the transparency of our universe. Here, we consider the  $\Lambda$ CDM model,  $E(z) = \frac{H(z)}{H_0} = \sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda + \Omega_k(1+z)^2}$  with  $\Omega_k = 1 - \Omega_\Lambda - \Omega_m$ . Following Ref. [26], we marginalize over  $\Omega_m$  and  $\Omega_\Lambda$  with  $\Omega_\Lambda \in [0, 1]$  and  $\Omega_M \in [0, 1]$ , and calculate the posterior probabilities of  $\Delta\tau$  by using the Bayesian approach

$$P(\Delta\tau|S, B) = \int_{\Omega_\Lambda} \int_{\Omega_M} P(\Omega_\Lambda, \Omega_M|B) P(\Delta\tau, \Omega_\Lambda, \Omega_M|S) d\Omega_\Lambda d\Omega_M, \quad (13)$$

where

$$P(\Omega_\Lambda, \Omega_M|B) = \frac{\exp(-\frac{\chi_B^2}{2})}{\int_{\Omega_\Lambda} d\Omega_\Lambda \int_{\Omega_M} d\Omega_M \exp(-\frac{\chi_B^2}{2})}, \quad (14)$$

and

$$P(\Delta\tau, \Omega_\Lambda, \Omega_M|S) = \frac{\exp(-\frac{\chi_S^2}{2})}{\int_{\Omega_\Lambda} d\Omega_\Lambda \int_{\Omega_M} d\Omega_M \int_0^{0.5} d\Delta\tau \exp(-\frac{\chi_S^2}{2})} \quad (15)$$

are the posterior probabilities of the set of model parameters given by BAO and SNIa data.

Assuming that the uncertainties on BAO and SNIa are Gaussian, we have

$$\chi_B^2 = \frac{1}{\sigma_{obs}^2} \left( \frac{A(z_2)}{A(z_1)} - \frac{A_{obs}(z_2)}{A_{obs}(z_1)} \right)^2, \quad (16)$$

$$\chi_S^2 = (\Delta\mu_{true} - \Delta\mu_{obs})^2 / \sigma_{obs}^2. \quad (17)$$

The constraints can then be obtained and results are shown in Fig. (1) and Tabs. (IV, V). The posterior distributions show that the universe is transparent between redshift regions  $0.106 - 0.2$ ,  $0.44 - 0.57$  and  $0.57 - 0.6$ , while it seems to be opaque at redshift regions  $0.2 - 0.35$ ,  $0.35 - 0.44$  and  $0.6 - 0.73$  since the best fit values of  $\Delta\tau$  are 0.061, 0.036 and 0.090 (0.052, 0.049 and 0.092 when systematic errors are considered) at these redshift regions, respectively. However, at the  $1\sigma$  confidence level,  $\Delta\tau = 0$  is still allowed. Thus, our result is consistent with a transparent universe at the  $1\sigma$  confidence level no matter whether systematic errors are included or not, although the cosmic opacity seems to show different properties at different redshift regions.

In addition, we find that our result at redshift region  $0.2 - 0.35$  is clearly different from what was obtained in [26] where a transparent universe is favored and at the 95% confidence

level  $\Delta\tau < 0.13$ . This difference may come from the fact that we use the latest SDSS DR7 BAO data while the SDSS DR5 is considered in [26]. Our result also differs from what was obtained using the Hubble data in [6] where  $\Delta\tau < 0.012$  at the 95% confidence level at redshift region  $0.2 - 0.35$ .

	best fit value	$1\sigma$	$2\sigma$	$3\sigma$
$\Delta\tau_{0.106-0.2}$	0	0.043	0.108	0.181
$\Delta\tau_{0.20-0.35}$	0.061	0.132	0.235	0.342
$\Delta\tau_{0.35-0.44}$	0.036	0.121	0.233	0.348
$\Delta\tau_{0.44-0.57}$	0	0.101	0.225	0.362
$\Delta\tau_{0.57-0.60}$	0	0.152	0.306	0.444
$\Delta\tau_{0.60-0.73}$	0.090	0.214	0.386	0.479

TABLE IV: The obtained  $\Delta\tau$  in different redshift regions.

	best fit values	$1\sigma$	$2\sigma$	$3\sigma$
$\Delta\tau_{0.106-0.2}(sys)$	0	0.058	0.153	0.247
$\Delta\tau_{0.20-0.35}(sys)$	0.052	0.139	0.268	0.390
$\Delta\tau_{0.35-0.44}(sys)$	0.049	0.146	0.282	0.411
$\Delta\tau_{0.44-0.57}(sys)$	0	0.129	0.286	0.444
$\Delta\tau_{0.57-0.60}(sys)$	0	0.184	0.371	0.475
$\Delta\tau_{0.60-0.73}(sys)$	0.092	0.245	0.423	0.492

TABLE V: The obtained  $\Delta\tau$  in different redshift regions with systematic errors included in SNIa.

### III. CONCLUSION

An opaque universe is an interesting possibility since it is capable of accounting for the SNIa dimming with no need of an accelerated cosmic expansion. In this paper, we discuss the constraints on the cosmic opacity from the latest BAO data, released from 6dFGS, SDSS, BOSS and WiggleZ survey, and the Union2 SNIa data. In our discussion, the effect of systematic errors in the Union2 SNIa is considered. The best fit values show that, whether

systematic errors are included or not, the data between the redshift regions  $0.106 - 0.20$ ,  $0.44 - 0.57$  and  $0.57 - 0.60$  favor a transparent universe, whereas, when the data between the redshift regions  $0.20 - 0.35$ ,  $0.35 - 0.44$  and  $0.60 - 0.73$  are used, an opaque universe is preferred. However, at the 68.3% confidence level,  $\Delta\tau = 0$  is still allowed by observations. Our result at the redshift region  $0.20 - 0.35$  is different from what was obtained in [26] where the SDSS DR5 BAO data are used and a transparent universe is found. This difference may come from that we use the latest SDSS DR7 BAO data. It also differs from the conclusion drawn from the Hubble data between redshift region  $0.20 - 0.35$  [6]. Although our result shows that the best-fit cosmic opacity oscillates between zero and some nonzero values as the redshift varies, a transparent universe is consistent with observations at the  $1\sigma$  confidence level.

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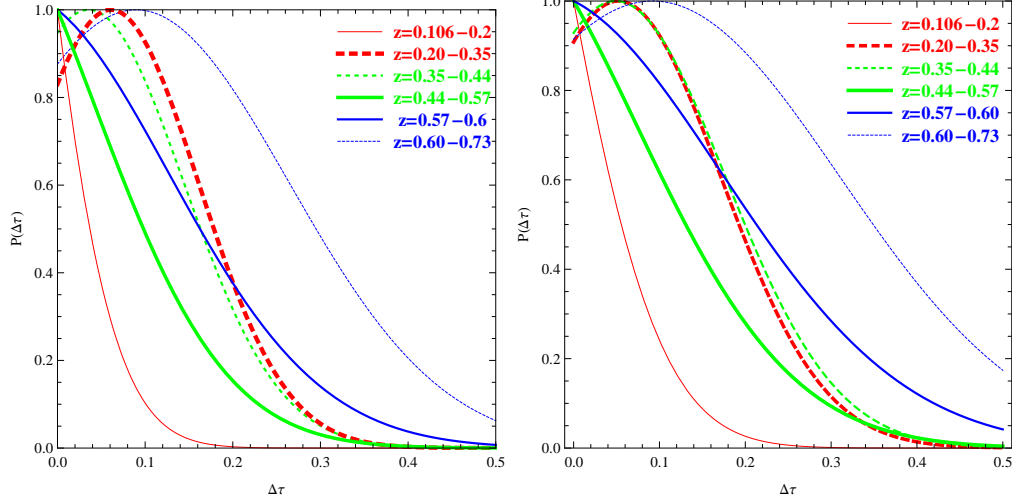


FIG. 1: The posterior probabilities of  $\Delta\tau$ . The left and right panels show the results without and with systematic errors, respectively

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